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Dust emission in massive star-forming regions with PRONAOS: the Orion and M17 molecular clouds

Xavier Dupac[1] and the PRONAOS collaboration

[1] *Centre d'Étude Spatiale des Rayonnements - CESR, 9 av. du Colonel Roche, BP 4346, F-31028 Toulouse Cedex 4, France*

Abstract

The balloon-borne submillimeter instrument PRONAOS has observed one square degree areas towards the Orion and M17 molecular clouds. The 2' - 3.5' resolution maps obtained in four wide wavelength bands between 200 μm and 600 μm, exhibit the dust distribution in these regions. We analyze the temperature and spectral index of the dust, and we show the anticorrelation between these two parameters. We derive estimations of the ISM column densities and masses in these regions.

1 INTRODUCTION

The high-mass star-forming regions of our Galaxy are known to be the site of complex physical and chemical processes, particularly involving dust grains. The submillimeter wavelength domain is particularly interesting to characterize dust properties. Dust emission in this spectral range is mainly due to big grains at thermal equilibrium (see, e.g., Désert *et al.* 1990), whose emission is usually modelled by the modified blackbody law, introducing the temperature and the spectral index of the dust. The temperature of a molecular cloud is a key parameter which controls (with others) the structure and evolution of the clumps, and therefore, star formation. Thus spectral imaging of molecular clouds can provide a large amount of knowledge about their structure and evolution, especially if the dust emission parameters are able to be properly derived on top of submillimeter intensities. Mapping of star-forming molecular clouds, as well as other dusty regions, has been performed by the PRONAOS balloon-borne experiment (PROgramme NAtional d'Observations Submillimétriques, see Buisson & Duran 1990 or Ristorcelli *et al.* 1998). We present here some results obtained on Orion and M17. The full analysis on Orion can be found in Dupac *et al.* 2001.

2 OBSERVATIONS AND DATA PROCESSING

PRONAOS (PROgramme NAtional d'Observations Submillimétriques) is a French balloon-borne submillimeter experiment, with a 2 m diameter telescope (Buisson & Duran 1990). The focal plane instrument SPM (Système Photométrique Multibande, see Lamarre *et al.* 1994) is composed of a wobbling mirror, providing a beam switching on the sky with an amplitude of about 6' at 19.5 Hz, and four bolometers cooled at 0.3 K. They measure the submillimeter flux in the spectral ranges 180-240 μm, 240-340 μm, 340-540 μm and 540-1200 μm, with sensitivity

Fig. 1. PRONAOS maps of Orion (top) and M17 (bottom) in band 1 (200 μm, top of each) and band 4 (580 μm, bottom of each). The color scale is logarithmic, and displays the positive reconstructed flux until -1.5 in log (Orion) or -1 (M17), then the deeper blue and purple colors display the negative noise features. The black lines in the color bars show the contour levels. The black box drawn in the 580 μm Orion map represents the area mapped by Ristorcelli *et al.* (1998).

to low brightness gradients of about 1 MJy/sr in band 4. The angular resolutions are 2' in bands 1 and 2, 2.5' in band 3 and 3.5' in band 4. The data which we present here were obtained during the second flight of PRONAOS in september 1996, at Fort-Sumner, New Mexico. The observing procedure is an altazimut scanning of the beam on the sky. The first processing applied to the data is correction from map distortion, taking into account the pointing of the telescope, including fine pointing errors due to the swinging of the gondola. Then we make the maps with the method described in Dupac *et al.* (2001), which is based on direct linear inversion on the whole map, using a Wiener matrix. This map-making process takes into account the beam sizes and profiles, the beam switching and the signal and noise properties to construct an optimal map. For the M17 data, we have used an improved method, in which we consider some noise not independent from the sky signal.

3 RESULTS AND ANALYSIS

We present in Fig. 1 the images of Orion M42 and M17 obtained in the two extreme photometric bands of PRONAOS-SPM. The noise level is about 4 MJy/sr rms in band 1 and 0.8 MJy/sr in band 4. However, due to the calibration uncertainty, the flux accuracy is not better than 5 % (1 σ) relative between bands (10-20 % absolute).

These maps enhance the very important intensity contrasts which exist in this kind of giant molecular complexes.

We assume the emission of the grains to obey the modified blackbody law:

$I_{\nu fit}(\lambda, T, n) = C.B_\nu(\lambda, T).\lambda^{-\beta}$

where λ is the wavelength, C a constant, T the temperature of the grains, β the spectral index and B_ν the Planck function.

The three parameters C, T and β, are adjusted with a least square fit.

From a detailed analysis of the temperature and spectral index spatial distribution in these molecular clouds, we deduce the following main results. The temperature varies roughly from 10 K to 80 K, the coldest dust being in the outskirts of the star-forming complex, mainly in the form of cold (early protostellar ?) clumps. The spectral index varies roughly from 1 to 2.5, the highest values being observed in the coldest areas. Indeed, it seems that exists an anticorrelation between the temperature and the spectral index. The correlation coefficient that we get in Orion is -0.9, and we obtain -0.8 in M17. Actually, the fit made on the PRONAOS submillimeter measurement induces an artificial amount of correlation, which is due to the relative insensitivity to spectral index variations of low-temperature submillimeter measurements, and to the relative insensitivity to temperature variations of high-temperature measurements. However, this artifact is clearly not enough to explain the anticorrelation found on the data. Therefore, this anticorrelation has to be an intrinsic property of the grains, or at least a property of the observed dust, when integrated on the ISM column. From further considerations, we rather support a fundamental explanation for this anticorrelation effect, involving the physical properties of the dust grains. Laboratory experiments (see Agladze *et al.* 1996 and Mennella *et al.* 1998) showed this effect on grains for temperatures down to

10 K. Agladze *et al.* (1996) measured absorption spectra of crystalline and amorphous grains between 0.7 and 2.9 mm wavelength. They deduced an anticorrelation between the power-law index β and the temperature in the temperature range 10-25 K, and attributed it to two level tunnelling processes. The measures of Agladze *et al.* are insufficient to justify our observation in the submillimeter spectral range, because absorption can be very different than in the millimeter range. Mennella *et al.* (1998) measured the absorption coefficient of cosmic dust analogue grains, crystalline and amorphous, between 20 μm and 2 mm wavelength, in the temperature range 24-295 K. They deduced an anticorrelation between T and β, and attributed it to two phonon difference processes. On our observations, we observe this effect down to about 15 K, thus we would need laboratory results on these low temperatures in the submillimeter range to fully understand the observations.

We also derived estimations of the column densities and masses in Orion and M17. For this we use the dust 100 μm opacity from Désert *et al.* (1990). It allows us to estimate the column density from the spectral intensity. We consider only the thermal emission of the big grains, which dominate widely in this spectral range, and we assume that the spectral index does not change in the PRONAOS spectral range. We take into account the variability of the dust spectral index of the different regions. This gives us a simple self-consistent model that allows us to estimate the column density N_H, as a function of the spectral intensity and the spectral index. We adopt the value of the opacity $\kappa_{100\mu m} = 0.361\ cm^2/g$ (per gram of total medium: gas and dust) at 100 μm, because this value is well constrained from IRAS data. This is calculated from the extinction curves given in Désert *et al.* The opacity κ is defined as $\frac{\tau}{N_H.m_H}$, thus the relation between the gas column density and the fit parameters is:

$N_H = \frac{C.\lambda^{-\beta}}{\kappa.m_H}$

where m_H is the proton mass and κ the gas and dust opacity. Then for the Désert *et al.* value of $\kappa_{100\mu m}$ we have:

$N_H = 1.67\ 10^{24}\ .\ \mathrm{C}\ .\ (100\ \mu m)^{-\beta}$

where N_H is the total column density in mass of the gas, in protons/cm^2, and C is in unit of μm^β. Then we compute the masses of the studied regions, assuming a distance of 470 pc (Orion) and 2200 pc (M17), by integrated the column density on the surface of the cloud. For example, we derive a total mass of the M17 complex of 18000 $M_\odot$. Some cold clouds that we observe in Orion and M17, near the warm star-forming area, could be gravitationally unstable.

As a small conclusion, we can say that these observations could be sustained by sensitive continuum observations in the millimeter domain, especially for the faint clouds evidenced, in order to better constrain the spectral index measurement of the cold dust. Also, infrared observations could be useful, particularly of the possible embedded protostars in those faint clouds.

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